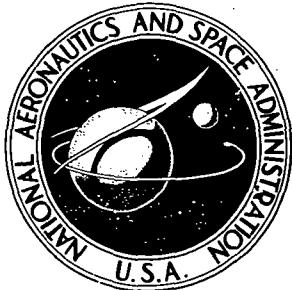


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SOLID-STATE AND FUSION RESISTANCE  
SPOT WELDING OF TD-NiCr SHEET

by Thomas J. Moore

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1973

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# SOLID-STATE AND FUSION RESISTANCE SPOT WELDING OF TD-NiCr SHEET

by Thomas J. Moore

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## SUMMARY

This program was designed to produce high-quality resistance spot welds in 0.4-millimeter (0.015-in.) thick TD-NiCr sheet. Four welding schedules were evaluated by using conventional resistance welding equipment. Both specially processed (unrecrystallized) and commercial TD-NiCr sheet were used. Welding parameters were selected in order to produce both solid-state and fusion resistance spot welds. All mechanical tests of the weldments were conducted on a single-spot lap joint specimen after it was postheated at 1200° C for 2 hours in hydrogen. The feasibility of producing solid-state resistance spot welds was also demonstrated in thicker, 1.6 millimeter (0.062 in.), TD-NiCr sheet.

Excellent results were obtained with a solid-state resistance-spot-welding schedule and specially processed sheet material. After postheating, the weld was indistinguishable from the parent material. In 1100° C stress-rupture shear tests, the welds were as strong as the parent material. Parent-material failure, rather than weld failure, took place in the stress-rupture tests and the other mechanical tests that included room-temperature and 1100° C tensile-shear tests and room-temperature fatigue tests.

Less satisfactory results were obtained with commercial sheet. A minimum-heat-input fusion spot weld could not be made without affecting the microstructure of the sheet. Solid-state spot welds, however, were produced without affecting sheet structure. But, for the solid-state welds, the weld plane was a stable grain boundary.

Unsatisfactory results were obtained when a conventional fusion spot weld was made in commercial sheet. Within the nugget the fine thoria dispersion and the large-grain structure of the sheet were lost. A valid stress-rupture curve could not be determined for this type of weldment.

## INTRODUCTION

The dispersion-strengthened alloy TD-NiCr (Ni-20Cr-2ThO<sub>2</sub>) has recently received consideration for high-temperature applications such as reentry heat shields for Space Shuttle vehicles (ref. 1). High creep strength and good oxidation resistance make this material quite attractive for these 1000° to 1200° C applications. But joining by fusion welding has been a major problem area with this material because melting destroys the fine thoria dispersion and the textured structure. The result is that the fusion zone is much weaker than TD-NiCr sheet. The joint efficiency is only about 30 to 50 percent (of parent-material strength) in elevated-temperature tensile tests (ref. 2). In some applications this strength may be adequate, but in many cases stronger welds are required. Thus, it has been a major challenge to produce welds in this material that are as strong as the parent material at elevated temperatures.

A recent review of joining methods for this material indicated that solid-state and fusion resistance spot welding (RSW) are probably the most promising joining methods for producing lap joints in TD-NiCr sheet (ref. 2). Where applicable, resistance spot welding is quite attractive for economic reasons and exceedingly attractive for production applications. Thus, the studies reported herein were conducted to evaluate more fully the potential of using resistance spot welding for joining TD-NiCr sheet.

Welding variables studied included electrode dome radius, welding force, welding current, and the number of heat cycles. The effect of faying surface preparation also was investigated. Commercial and specially processed (unrecrystallized) TD-NiCr sheet were utilized in order to determine the effect of the metallurgical condition of the starting material. Both solid-state and fusion resistance spot welds were evaluated.

Weld quality was evaluated by metallographic techniques and by mechanical property tests. The following mechanical tests were conducted on single-spot lap joints in 0.4-millimeter (0.015-in.) TD-NiCr sheet:

- (1) 1100° C Stress-rupture shear tests (to 1000 hr)
- (2) 1100° C Tensile-shear tests
- (3) Room-temperature fatigue tests (tension-tension,  $\sigma_{\min}/\sigma_{\max} = 0.2$ )
- (4) Room-temperature tensile-shear tests

Based upon results of these tests, conclusions are offered regarding the effect of the resistance spot-welding schedule and the starting condition of the TD-NiCr sheet on weld quality. In addition, an attempt was made to demonstrate the feasibility of producing solid-state resistance spot welds in thicker TD-NiCr sheet, 1.6 millimeter (0.062 in.).

## EXPERIMENTAL PROCEDURE

### TD-NiCr Sheet

TD-NiCr material has a nominal composition of nickel - 20-weight-percent chromium - 2-weight-percent thoria. Elevated-temperature strengthening is produced from a combination of factors (ref. 3) that include (1) the fine thoria dispersion in a Ni-Cr matrix, and (2) a stable textured microstructure with large pancake-shaped grains. This structure is produced during a recrystallization anneal after a thermomechanical processing cycle. Both a specially processed and a commercially processed TD-NiCr sheet were used in this program. This welding study was designed primarily to produce welds in 0.4-millimeter (0.015-in.) material. But a few runs were made in a thicker material, 1.6 millimeters (0.062 in.).

Specially processed (SP) TD-NiCr. - The manufacturing process for TD-NiCr sheet (from ref. 3) is shown in figure 1. Note that when the material is removed from the processing cycle, directly after warm rolling, it is unrecrystallized. In this specially processed condition (hereinafter termed "SP"), TD-NiCr has a very fine grain size that cannot be resolved by light microscopy (refs. 3 and 4). This material has relatively low high-temperature strength, but it has good ductility at intermediate temperatures ( $\sim 750^{\circ}\text{C}$ ).

The SP material was selected as a starting material since the weld line can be eliminated by postheating, as demonstrated in hot press diffusion welding of TD-NiCr sheet (ref. 4). Postheating recrystallized the SP material to the condition of commercial TD-NiCr. In that study, 1.6-millimeter (0.062-in.) sheet was used, as compared to 0.4-millimeter (0.015-in.) material for this program. Since the chemical composition, the microstructure, and the thermomechanical processing cycle were essentially the same for both thicknesses, it was felt that the metallurgical behavior would be similar.

Commercial TD-NiCr. - TD-NiCr sheet 0.4 millimeter (0.015 in.) thick produced by the standard commercial process (hereinafter termed "commercial" material) was also used as starting material. This commercial material also is processed as shown in figure 1. It differs from SP material only in the fact that it has been given a recrystallization anneal at  $1180^{\circ}\text{C}$  for 2 hours after warm rolling (ref. 3). The commercial material thus has the large recrystallized grains and textured microstructure that are necessary for optimum strength at elevated temperatures.

### Welding Procedures

After a series of preliminary experiments, three resistance-spot-welding schedules were developed in this study for lap welding 0.4-millimeter (0.015-in.) TD-NiCr sheet.

These were designated as schedules A, B, and C. Samples prepared with a more conventional fusion-welding schedule, which was developed by a commercial source, were included in this evaluation for comparison. This welding schedule was designated as schedule D. Best results for spot welds made by schedules A, B, C, and D were obtained when the procedures and settings shown in table I were used. For each welding schedule a number of lap joint test specimens of the design shown in figure 2 were produced. A brief description of the metallurgical objectives for the spot welds developed under the four schedules is as follows:

Schedule A. - Schedule A was used to produce a solid-state resistance spot weld in SP TD-NiCr. This weld is produced without recrystallizing the parent material. Post-heating is employed to recrystallize the parent material and to promote grain growth across the weld line.

Schedule B. - Schedule B was used to produce a spot weld with minimum heat input in commercial TD-NiCr. These welds usually involved a small amount of melting. But sometimes a solid-state weld was produced by using the same parameters.

Schedule C. - Schedule C was used to produce a solid-state resistance spot weld in commercial material.

Schedule D. - Schedule D was used to produce a conventional resistance spot weld in which a molten nugget was intentionally produced.

In the following paragraphs the effect of faying surface preparation and the weld schedule development studies are discussed in more detail:

Schedules A, B, and C. - In developing the welding schedules shown in table I a 400-kilovolt-ampere, single-phase resistance welding machine was used. Early in the program, it was found that high-quality solid-state welds could be produced by simply using a chemical etching procedure on as-received (120-grit) sanded surfaces. Therefore, the surface preparation method shown in figure 3 was used. Excellent results were obtained with class III copper electrodes, in that no sticking of the electrode to the work pieces was experienced for schedules A and B. With schedule C, very slight to no sticking was encountered. Pneumatic force proved to be an important variable in the development of  $I^2R$  heating between the faying surfaces. For example, with all other variables held constant for schedule B welds, progressively decreasing the air force from 10 kilonewtons (2250 lb) to 6.7 kilonewtons (1510 lb) produced excessive  $I^2R$  interfacial heating and a large molten nugget. Gross thoria agglomeration, weld cracking, and excessive electrode indentation resulted.

Heat input at the weld interface also depends on the welding current and the number of heat cycles. A typical welding current trace (schedule B) for the single-phase resistance spot-welding machine is shown in figure 4. The phase-shift heat setting was used to control the peak welding current. A current analyzer was used to measure peak welding current and to count the number of half-cycles. Control of welding current was

essential in order to produce high-quality welds. One-cycle schedule B welds in commercial material at 27.9 kiloamperes (peak) were sound and strong. But at 29.9-kiloamperes peak welding current, overheating and weld cracking were produced. For schedule C welds, which were made with 15 weld current cycles, strong high-quality welds were produced at 24.2 kiloamperes. But at 23.0 kiloamperes, much weaker welds were produced.

Consistent and highly reproducible welds were made by using the selected weld schedules A, B, and C of table I.

Schedule D. - These spot welds were produced by using a 100-kilovolt-ampere, three-phase resistance welding machine. The faying-surface preparation procedure that was used is shown in figure 5. Wet polishing to 320-grit to promote surface-to-surface contact was done in the hope of avoiding both overheating at the weld interface and parent material expulsion. After a number of trial welds were made, the electrode material, diameter, and tip radius and the welding schedule shown in table I were selected. This selection was based on minimum tendency for electrode sticking to the workpieces and on room-temperature tensile test results. Even with the best settings, however, electrode sticking was often a problem, as shown by copper deposits on the workpieces. The copper deposits were removed by hand sanding prior to postheating. A larger radius dome on the upper electrode (see table I) and/or increased pneumatic force would minimize this problem.

The form of the current trace for a single-impulse three-heat-cycle weld for the three-phase machine is shown in figure 6. (Compare this trace with the sine wave form shown for the single-phase machine (fig. 4).) The welding current for the three-phase machine (fig. 6) shows a gradual buildup for about the first six peaks. It then tends to level off.

## Examination of Spot Welds

Metallography. - In developing the specimen preparation and welding parameters for the four welding schedules, metallography was used extensively to evaluate weld quality. Spot welds were sectioned as indicated in figure 2 in both the as-welded and postheated ( $1200^{\circ}\text{C}$ , 2 hr, hydrogen) conditions. In addition, many mechanically tested welds were examined in order to determine mode of fracture, weld microstructure, and weld quality. A single etching procedure was used in preparing all specimens for metallographic examination. This consisted of immersion in a solution of 100 cubic centimeters  $\text{H}_2\text{O}$ , 2 grams  $\text{Cr}_2\text{O}_3$ , 10 cubic centimeters  $\text{H}_2\text{SO}_4$ , and an electrolytic etch at 3 volts dc for about 8 seconds.

Weld spot diameter. - Analysis of the strength data was based on weld shear-stress rather than on the load-carrying ability of the spot welds. Thus, weld spot size was determined in order to evaluate weld integrity in a qualitative manner and to more accurately give a relative rating to schedule A, B, C, and D spot welds. Scale measurements were made in order to determine spot diameter from tested tensile-shear and stress-rupture shear specimens. In cases where failure occurred away from the weld, spot size could not be measured in this manner. For the tested fatigue specimens, all failures were located in the parent material in front of the spot. So, the fatigue specimens were not used in the determination of spot diameter. Spot diameter determinations are believed to be reasonably accurate even though some spot welds were somewhat elliptical, rather than round. In these cases, an approximate diameter was estimated and used for comparison. An average value of spot diameter was determined for schedule A, B, C, and D welds; and this value (shown in table I) was used for all calculations of shear stress at the weld.

Note in table I that the weld spot diameters are rather large, being about 10 to 14 times the sheet thickness. In developing the welding schedules, emphasis was placed on producing particular microstructures. Spot size was a secondary consideration. With a given load on a single spot-welded lap joint (fig. 2) and spot diameter, as shown in table I, the ratio of weld shear stress to parent-material tensile stress ranges from 0.40 (for schedule C) to 0.75 (for schedule D).

Deformation. - Typical deformation values are presented in table I in terms of percent change in thickness  $\% \Delta t$  at the center of the spot welds. For the solid-state spot welds, the  $\Delta t$  values are small: 0.8 percent for schedule A and 2.5 percent for schedule C. But for the fusion spot welds, the  $\% \Delta t$  values are much higher: 8 percent for schedule B and 13 percent for schedule D.

## Mechanical Testing

Single-spot lap weldments of the design shown in figure 2 were subjected to the following tests (in air):

- (1)  $1100^{\circ}$  C Stress-rupture shear tests (to 1000 hr)
- (2)  $1100^{\circ}$  C Tensile-shear tests
- (3) Room-temperature tensile-shear tests
- (4) Room-temperature fatigue tests (tension-tension,  $\sigma_{\min}/\sigma_{\max} = 0.2$ )

Specimens resulting from each of the four weld schedules were included. All mechanical testing was conducted after the specimens were postheated at  $1200^{\circ}$  C for 2 hours in hydrogen. Prior to the postheating, residual copper (if present) was removed by hand sanding from the sheet/electrode contact areas. The  $1100^{\circ}$  C stress-rupture shear tests were conducted with deadweight loading. The  $1100^{\circ}$  C tensile-shear tests were conducted

after a 5-minute hold-time at the test temperature. Both the 1100° C and room-temperature tensile-shear tests were run at a crosshead speed of 1.3 millimeters (0.05 in.) per minute. Room-temperature fatigue tests were run in the tension/tension mode.

## RESULTS

### Spot-Weld Microstructures

In this section, the spot-weld microstructures that were obtained with welding schedules A, B, C, and D are presented. Each of these welding schedules was used to produce spot welds of particular metallurgical characteristics, as noted in the section EXPERIMENTAL PROCEDURE. The metallurgical condition at the spot weld should be borne in mind when the results of the mechanical tests are reviewed in the next section. The welding machine settings used in this study are not meant to be firm requirements. Other settings which would produce similar metallurgical results should produce similar spot-weld quality.

Schedule A. - Cross sections of typical schedule A solid-state spot welds in SP TD-NiCr sheet are shown in figure 7. Note in figure 7(a) that there is no apparent deformation and little or no evidence of heat effects. This spot weld was made in 11 heat cycles (table I) while preserving the unrecrystallized structure in the SP parent material. Only two small (light etching) recrystallized grains are evident in the as-welded condition, and the weld line is not visible (fig. 7(b)). Post heating at 1200° C for 2 hours in hydrogen produced the conventional, large-grained, recrystallized structure shown in figure 7(c). Grain growth across the initial weld interface is complete, and there is no metallographic evidence of a weld. That is, the region of the solid-state resistance spot weld is indistinguishable from the parent material. Reproducibility of this weld microstructure was excellent. Similar weld microstructures were observed for all other schedule A specimens sectioned after mechanical testing.

Schedule B. - A typical spot weld made by using this schedule with commercial sheet is shown after postheating in figure 8. This schedule usually produced fusion welds with a slight indentation from the electrodes (fig. 8(a)) and a mottled microstructure (fig. 8(b)). The postheated microstructure shown in figure 8(b) is similar to the as-welded microstructure (not shown). The dark areas within the nugget (fusion zone) offer evidence of thoria agglomeration. The texture produced in the TD-NiCr sheet by thermo-mechanical processing also has been lost as a result of the fusion weld. Physical evidence of melting was offered by the emanation of tiny sparks during welding. This resulted in the presence of tiny slivers of expelled material at the faying surfaces near the spot weld.

A few schedule B welds were of the solid-state type, similar in microstructure to the schedule C weld shown in figure 9. Evidently, this minimum-heat-input weld can be either a fusion or solid-state type. Further development and refinement of procedure and weld schedule probably could not guarantee a reproducible weld microstructure because subtle differences in surface roughness or waviness of thickness of the sheet could affect interfacial heating. Weld time less than 1/60 second is just too short an interval within which to precisely reproduce interfacial heating effects.

Schedule C. - The macrostructure in figure 9(a) shows a cross section of a typical schedule C solid-state spot weld in commercial sheet. A conventional spot-weld nugget was not produced nor is there any noticeable electrode indentation. The parent-material microstructure was not disturbed, and the weld line is essentially a grain boundary (fig. 9(b)). This is a stable structure. No grain growth took place across the weld line during postheating.

In one case, a schedule C spot weld showed some evidence of intergranular melting near the weld line. This will be illustrated in the next section, Mechanical Tests.

Schedule D. - This schedule produced a fusion weld with some electrode indentation and a well-defined nugget, as shown in figure 10(a). No cracks were found, and only trace amounts of molten material were expelled between the faying surfaces. In the as-welded condition, there is evidence of  $\text{ThO}_2$  agglomeration (dark areas) within the nugget (fig. 10(b)). Also within the nugget, the grain structure and texture of the original parent material were destroyed. In the postheated condition (fig. 10(c)), clearly defined white regions appear near the initial interface. These white areas are believed to be completely free of thoria particles (refs. 5 and 6).

## Mechanical Tests

Mechanical test results are presented and discussed in this section. All test results are shown graphically in terms of shear stress on the weld rather than load. This approach is believed to give a better assessment of weld integrity. Metallographic analysis of typical fractured specimens is included in order to better understand the fracture mechanism and to evaluate weld quality.

Stress-rupture shear tests. - Stress-rupture shear test results obtained for post-heated single-spot lap joints at  $1100^{\circ}\text{C}$  are shown in table II. The types of failures listed in table II are shown in figure 11. Note that there was very little tendency for joint rotation. This was because of the high creep strength of the TD-NiCr sheet. As a result, relatively pure shear stress was imposed on the spot welds in the stress-rupture shear tests.

Spot-weld shear stress values for schedule A, B, C, and D welds are plotted against hours-to-rupture in figure 12. For comparative purposes, the 1090° C stress-rupture shear strength of 1.6-millimeter (0.062-in.) sheet (obtained from ref. 4) is shown as a line in figure 12. Since it is assumed that properties of the unwelded 0.4-millimeter (0.015-in.) commercial TD-NiCr sheet used in this study are the same as those of the 1.6-millimeter (0.062-in.) sheet evaluated in reference 4, properties of the 1.6-millimeter (0.062-in.) sheet are referred to hereinafter as "parent material" properties. All schedule A stress-rupture shear specimens failed in the parent material (table II and fig. 11(d)). Figure 13(a-1) shows a typical weld region microstructure for a schedule A spot weld after stress-rupture testing. The weld is sound, and the parent material shown in figure 13(a-2) exhibits a typical stress-rupture failure (ref. 6) for a TD-NiCr sheet. Considering weld spot size (table I), the ratio of weld shear stress to parent-material tensile stress was about 0.6. On this basis and because the weld test points are well above the shear-stress curve for 1.6-millimeter (0.062-in.) TD NiCr parent material shown in figure 12, the stress-rupture shear strength of schedule A welds is considered to be equivalent to that of the parent material at 1100° C.

Weld schedule B test points were above the parent-material curve except for a 1-hour test point (fig. 12). But the failure mode was usually by shear at the weld (fig. 11(a) and table II). Earlier, in the section Spot Weld Microstructures, it was pointed out that the schedule B welding parameters sometimes produced solid-state rather than fusion spot welds. Examination of two of the strongest welds (B-1 and B-2) showed that these were indeed solid-state spot welds. The other schedule B welds, which had excellent strength, are considered as satisfactory for 1100° C service. The fracture microstructure of fusion spot weld B-4 in figure 13(b-1) shows shear failure at the weld. A solid-state spot-weld specimen (B-2) that was unloaded after 508 hours is shown in figure 13(b-2).

Most of the schedule C test points fall on or slightly above the parent-material stress-rupture shear curve. The one exception is a 0.8-hour failure below the curve. These results indicate that the schedule C welds had satisfactory stress-rupture properties. However, the fracture mode varied (table II). One specimen failed by weld shear (fig. 11(a)), and two others failed in the parent material near the weld (fig. 11(c)). Another failed by a combination of parent-metal cracking and weld shear (fig. 11(b)). Figure 13(c) shows a portion of the weld microstructure for specimen C-3 in which the dark grain boundaries and the dark matrix material are believed to be evidence of agglomerated thoria. Despite the evidence that some thoria agglomeration occurred, specimen C-3 did not fail in the region shown in figure 13(c). Failure occurred in the parent material away from the spot weld (not shown). However, schedule C was designed to produce solid-state spot welds. For specimen C-3, the dark areas at the grain boundaries and in the matrix indicate that localized melting occurred. Further developmental

efforts could probably eliminate this small degree of melting. For example, reducing the number of heat cycles from 15 to perhaps 10 might eliminate this potential problem area.

The schedule D test points in figure 12 are below the parent-material curve. Indeed, a valid stress-rupture curve cannot be drawn for the schedule D test data because of the scatter of the rupture data. Within a given weld shear-stress range, failure sometimes occurred on loading and sometimes after 400 hours. All failures were smooth-face shear at the weld (fig. 11(a)). Even for the cases in which the test was stopped before rupture, the weldments failed by smooth-face shear on cooling under no load. This plane of weakness apparently results from the absence of thoria near the initial interface (defined by the white bands shown in fig. 10(c) and the white-grained region at the initial interface shown in fig. 13(d)) and the loss of the large-grain structure required for high-temperature strength. On the basis of these stress-rupture results, the schedule D welds are considered unsatisfactory for 1100° C service where high-strength joints are required. In addition, thermal-cycling behavior of the schedule D welds would probably be very poor because of the plane of weakness at the weld.

Tensile-shear tests. - Both the 1100° C and room-temperature test results are presented in this section. The test data are listed in table III and plotted in figure 14. Tensile-shear specimens, tested at 1100° C, are shown in figure 15 to illustrate the fracture modes described in table III. Note in figure 15 that the stiff parent material did not allow rotation of the joint. Thus, relatively pure shear-loading was applied to the welds in the 1100° C tests. In these elevated-temperature tests, best results were achieved for the schedule A weldments because failure occurred in the parent material (fig. 15(b)) at an average weld shear stress of 47.4 N/m<sup>2</sup> (6.82 ksi). The weld microstructure was similar to that shown in figure 13(a-1). Schedule B, C, and D weldments were somewhat weaker and generally failed by weld shear (figs. 14 and 15(a)). A schedule B fusion spot weld that pulled a partial button is shown in figure 16(a). Weld shear with partial parent-metal pullout is shown for the schedule C solid-state spot weld in figure 16(b). The failure mode for the schedule D welds is similar to that shown in figure 13(d), a smooth-face shear fracture at the initial interface.

In the room-temperature tensile-shear tests, the average calculated shear stress at fracture was about 186 kN/m<sup>2</sup> (27 ksi) for both schedule A and B welds (table III and fig. 14). Schedule C gave a somewhat lower value, 135 kN/m<sup>2</sup> (19.6 ksi); and schedule D gave 173 kN/m<sup>2</sup> (25.1 ksi). All these specimens failed by button pullout, as shown in figure 17. Because of this failure mode, the spot welds were not severely tested in shear. Thus, these tests were not discriminatory in the determination of weld quality.

Fatigue tests. - The results of the room-temperature tests are shown in table IV and are plotted in figure 18. In the range of 10<sup>4</sup> to 10<sup>5</sup> cycles, there is some difference in fatigue strength between the different welding schedules, with the schedule B welds being consistently stronger than the others. But at 10<sup>6</sup> cycles, the fatigue strength tends

to be similar for the schedule A, B, C, and D spot welds. In no case did weld failure occur. The fatigue cracks in every case were located in the parent material at the periphery of the spot weld, as shown in figure 19. A section of a typical transgranular fatigue failure is shown in figure 20. These fatigue tests did show that the spot welds made under all four schedules were not prone to fatigue failure at room temperature under the cyclic conditions used here.

## DISCUSSION

Completely satisfactory results were obtained by using a solid-state resistance-spot-welding technique (schedule A) and SP (unrecrystallized) TD-NiCr sheet. After postheating ( $1200^{\circ}$  C, 2 hr), the welds were indistinguishable from the parent material. Reproducibility of this weld microstructure was excellent. Stress-rupture shear strength of the schedule A spot welds was equal to that of the parent material. And in  $1100^{\circ}$  C tensile-shear, room-temperature tensile-shear, and fatigue tests, failure always took place away from the weld.

Results obtained with a minimum-heat-input fusion spot weld in commercial sheet (schedule B) showed promise, but there was some thoria agglomeration and the grain structure of the parent material was changed at the weld. Although the stress-rupture shear strength was good, failure usually occurred at the weld. Schedule B welds appeared best in fatigue strength in room-temperature tests. Weakening effects produced by melting apparently are not harmful in these room-temperature tests. In developing the schedule B welding procedure, some weld cracking was produced with small changes in weld settings. This shows that, with a fusion welding schedule, weld cracking is a potential problem.

For schedule C, solid-state resistance spot welds in commercial sheet, the weld line was essentially a grain boundary. Although there was no loss of the thoria dispersion or grain structure, the lack of grain growth across the weld line was undesirable. With commercial sheet, postheating did not promote grain growth across the weld line. The elevated-temperature stress-rupture shear and tensile-shear properties were good although they were generally lower than those of schedules A and B. In some cases, schedule C spot welds fractured at the weld in elevated-temperature tests. For spot welding commercial TD-NiCr sheet to itself, however, schedule C is preferred over schedule B because the former is a solid-state welding process that preserves the metallurgical structure of the TD-NiCr sheet and because this weld microstructure is believed to be more reproducible.

The fusion spot weld produced with schedule D with a conventional weld nugget in commercial sheet was less desirable than the others for several reasons. Within the fusion zone, the fine thoria distribution and the large-grain structure were destroyed.

A plane of weakness at the weld was the fracture location for all 1100° C stress-rupture shear and tensile-shear tests. A valid stress-rupture curve could not be determined because of extreme scatter in the data.

## CONCLUDING REMARKS

Two major factors were responsible for the success achieved in the best resistance spot welds in 0.4-millimeter (0.015-in.) TD-NiCr sheet (i.e., using schedule A). First was the selection of specially processed (unrecrystallized) TD-NiCr sheet. Second was the selection of a welding schedule that produced a solid-state spot weld without recrystallizing the specially processed sheet. Postheating produced grain growth across the weld line during recrystallization of the sheet.

Similar results were obtained in thicker gage, 1.6 millimeter (0.062 in.), sheet. The welding parameters that were used for the 1.6-millimeter (0.062-in.) thick, specially processed (unrecrystallized) sheet are shown in the appendix. And the weld microstructure in the postheated condition is shown in figure 21(a). This weld microstructure is quite similar to that shown earlier for the thinner sheet (fig. 7(c)).

Feasibility was also established for producing solid-state resistance spot welds in 1.6-millimeter (0.062-in.) commercial TD-NiCr sheet. The weld microstructure is shown in figure 21(b), and the welding parameters are shown in the appendix. Similar welds which were made in the main portion of this study, in 0.4-millimeter (0.015-in.) commercial sheet (fig. 9(b)), showed considerable promise.

The principles used herein to successfully weld TD-NiCr sheet are recommended for use with other dispersion-strengthened and difficult-to-weld materials. Specifically, it is important to choose the best metallurgical starting condition for the welding process which subsequently will be used. Resistance-spot-weld schedules which will produce a solid-state spot weld should be considered. Resistance spot welding should not be thought of strictly as a fusion process in which a molten nugget is developed. Postheating can be used effectively to improve weld quality.

Although it was beyond the scope of this study, it is believed that solid-state resistance seam welds could readily be produced in TD-NiCr sheet. All that would be necessary is to substitute circular electrode wheels for the spot-welding electrodes. Studies of solid-state resistance seam welding are highly recommended where a continuous solid-state weld is required.

## CONCLUSIONS

This study was designed to determine the applicability of resistance spot welding for welding 0.4-millimeter (0.015-in.) TD-NiCr sheet. Four welding schedules were developed. In one schedule, specially processed (unrecrystallized) sheet was used. Commercial sheet was used for the other three welding schedules. Both solid-state and fusion spot welds were made. Weld quality was evaluated metallographically and by mechanical testing of single-spot lap joints. Included were 1100° C stress-rupture shear and tensile-shear tests and room-temperature tensile-shear and fatigue tests. Prior to mechanical testing, all weldments were postheated at 1200° C for 2 hours in hydrogen. The prime results and conclusions are as follows:

1. A solid-state resistance-spot-welding schedule in combination with specially processed TD-NiCr sheet resulted in the best quality welds. With this procedure, all metallographic evidence of the weld was eliminated during postheating (1200° C, 2 hr). Stress-rupture shear strengths of the welds were equivalent to that of the parent material. In addition, parent-material failure occurred away from the weld in the tensile-shear tests at room temperature and 1100° C and in the fatigue tests.
2. In commercial TD-NiCr sheet, overall spot-weld quality was generally satisfactory although not as good as that obtained with the specially processed material. Best results were achieved with the following weld schedules:
  - a. A solid-state welding schedule produced spot welds with good stress-rupture shear strength. Tensile-shear and fatigue strengths also were good. This solid-state welding schedule is preferred over the minimum-heat-input fusion spot weld because the solid-state welding schedule does not change parent-material microstructure at the weld. Also any potential weld cracking problem associated with melting can be avoided.
  - b. A minimum-heat-input fusion-spot-welding schedule gave good stress-rupture shear, tensile-shear, and fatigue properties. But shear failures at the weld in the stress-rupture shear tests were evidence that the thoria dispersion and the grain structure were adversely affected.
3. Fusion spot welds with a well-defined nugget in commercial TD-NiCr sheet are less satisfactory for elevated-temperature service. Erratic stress-rupture properties and a smooth-face, weld shear fracture in the 1100° C stress-rupture shear and tensile-shear tests were observed.

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Cleveland, Ohio, February 7, 1973,  
502-21.

**APPENDIX - RESISTANCE-SPOT-WELDING SCHEDULE FOR SINGLE-SPOT  
LAP WELDS IN 1.6-MILLIMETER (0.062-IN.) SPECIALLY  
PROCESSED AND COMMERCIAL TD-NiCr SHEET**

**Constants**

Faying surface preparation: Chemically etched, stored in Freon (see fig. 3)

Welding atmosphere: air

Welding machine: 400 kVA, single phase

Welding electrodes: Class III copper alloy, 12.7-mm (0.5-in.) diameter with a 305-mm (12-in.) dome radius

Pneumatic force: 13.0 kN (2860 lb)

Control settings (single impulse)

Percent heat: <20

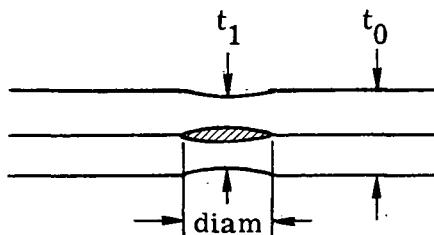
Squeeze cycles: 120

Hold cycles: 30

**Variables**

| Parent material     | Heat cycles | Peak welding current, kA | Deformation, <sup>a</sup> % $\Delta t$ | Spot diameter <sup>b</sup> |      |
|---------------------|-------------|--------------------------|--|----------------------------|------|
|                     |             |                          |  | mm                         | in.  |
| Specially processed | 11          | 18.8                     | None                                   | 6.9                        | 0.27 |
| Commercial          | 15          | 19.5                     | 0.2                                    | 7.2                        | .28  |

$$\text{a} \frac{\% \Delta t}{\% \Delta t} = \frac{t_0 - t_1}{t_0}$$



<sup>b</sup>Measured from a single photomicrograph. Weld sectioned as shown in fig. 2.

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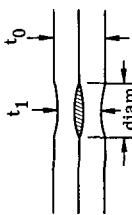
TABLE I. - RESISTANCE-SPOT-WELDING SCHEDULES FOR SINGLE-SPOT LAP WELDS IN 0.4-MILLIMETER (0.015-IN.) TD-NiCr SHEET

[All welds were single-impulse type, made in air, with copper alloy electrodes.]

| Welding schedule | Parent material <sup>a</sup> | Faying surface preparation <sup>b</sup> | Welding machine | Copper alloy electrodes (class III) |       | Pneumatic force |                  | Control settings |      | Peak welding current, kA | Deformation, % $\Delta t$ | Spot diameter <sup>e</sup> , mm | In.  |
|------------------|------------------------------|---|-----------------|-------------------------------------|-------|-----------------|------------------|------------------|------|--------------------------|---------------------------|---------------------------------|------|
|                  |                              |   |                 | Type                                | kVA   | Diameter, mm    | Dome radius, in. | kN               | lb   | Percent heat             | Squeeze cycles            | Heat cycles <sup>c</sup>        |      |
| A                | SP                           | CE, F                                   | Single phase    | 400                                 | 12.7  | 0.5             | 305              | 12               | 10.0 | 2250                     | <20                       | 120                             | 11   |
| B                | C                            | CE, F                                   | Single phase    | 400                                 | 12.7  | .5              | 203              | 8                | 10.0 | 2250                     | 26                        | 120                             | 1    |
| C                | C                            | CE, F                                   | Single phase    | 400                                 | 12.7  | .5              | 305              | 12               | 10.0 | 2250                     | <20                       | 120                             | 15   |
| D                | C                            | C, P, W                                 | Three phase     | 100                                 | f7.9  | f.31            | f51              | f2               | 6.5  | 1450                     | 30                        | 25                              | 3    |
|                  |                              |   |                 |                                     | g15.7 | g.62            | g305             | g12              |      |                          |                           | 25                              | 10.4 |
|                  |                              |   |                 |                                     |       |                 |                  |                  |      |                          |                           | 25                              | 13.0 |
|                  |                              |   |                 |                                     |       |                 |                  |                  |      |                          |                           | 4.1                             | 4.1  |
|                  |                              |   |                 |                                     |       |                 |                  |                  |      |                          |                           | 16                              | 16   |

<sup>a</sup>SP = specially processed (unrecrystallized) material. C = commercial (recrystallized) material.<sup>b</sup>C, E, F = chemically etched, stored in Freon (fig. 3). C, P, W = cleaned, polished with 320-grit paper, wiped with solvent (fig. 5).<sup>c</sup>Note in figs. 4 and 6 that the sine wave heat cycle for the single-phase machine is quite different than the heat cycle for the three-phase machine.

$$\% \Delta t = \frac{t_0 - t_1}{t_0} \times 100$$



<sup>e</sup>Average values based on measurements of tested weldments.  
fUpper electrode.  
Lower electrode.

TABLE II. - STRESS-RUPTURE SHEAR TEST RESULTS FOR SINGLE-  
SPOT LAP JOINTS IN 0.4-MILLIMETER (0.015-IN.) TD-NiCr

SHEET AT 1100° C

[All specimens were postheated at 1200° C for 2 hr in hydrogen prior to testing.]

| Weld schedule <sup>a</sup><br>and number | Load |     | Weld shear stress |      | Life,<br>hr      | Fracture <sup>b</sup> |
|--|------|-----|-------------------|------|------------------|-----------------------|
|  | N    | lb  | MN/m <sup>2</sup> | ksi  |                  |                       |
| A-1                                      | 622  | 140 | 38.8              | 5.62 | 29               | PM, away from weld    |
| A-2                                      | 578  | 130 | 36.0              | 5.22 | 16               | PM, near weld         |
| A-3                                      | 534  | 120 | 33.2              | 4.82 | 592              | PM, away from weld    |
| A-4                                      | 490  | 110 | 30.7              | 4.42 | 665              | PM, away from weld    |
| B-1                                      | 622  | 140 | 37.6              | 5.45 | 19               | Weld shear            |
| B-2                                      | 534  | 120 | 32.2              | 4.67 | 508+             | Test stopped          |
| B-3                                      | 490  | 110 | 29.6              | 4.28 | 88               | PM, away from weld    |
| B-4                                      | 445  | 100 | 26.9              | 3.89 | 1.0              | Weld shear            |
| B-5                                      | 423  | 95  | 25.6              | 3.70 | 72               |                       |
| B-6                                      | 401  | 90  | 24.2              | 3.50 | 451              |                       |
| B-7                                      | 378  | 85  | 22.8              | 3.30 | 364              |                       |
| C-1                                      | 622  | 140 | 25.2              | 3.64 | .8               |                       |
| C-2                                      | 578  | 130 | 23.4              | 3.39 | 193              | PM, near weld         |
| C-3                                      | 534  | 120 | 21.6              | 3.13 | 384              | PM, near weld         |
| C-4                                      | 490  | 110 | 19.7              | 2.86 | 308              | PM crack, weld shear  |
| C-5                                      | 445  | 100 | 18.0              | 2.61 | 839+             | Test stopped          |
| D-1                                      | 245  | 55  | 18.4              | 2.67 | <sup>c</sup> FOL | Weld shear            |
| D-2                                      | 231  | 52  | 17.5              | 2.53 |                  |                       |
| D-3                                      | 222  | 50  | 16.8              | 2.43 | 2.0              |                       |
| D-4                                      | 200  | 45  | 15.1              | 2.19 | .8               |                       |
| D-5                                      | 200  | 45  | 15.1              | 2.19 | 1.7              |                       |
| D-6                                      | 200  | 45  | 15.1              | 2.19 | 522+             | Test stopped, WSOC    |
| D-7                                      | 191  | 43  | 14.4              | 2.09 | 1125+            | Test stopped, WSOC    |
| D-8                                      | 187  | 42  | 14.1              | 2.04 | 814+             | Test stopped, WSOC    |
| D-9                                      | 178  | 40  | 13.4              | 1.94 | .5               | Weld shear            |
| D-10                                     | 156  | 35  | 11.7              | 1.70 | 475+             | Test stopped, WSOC    |

<sup>a</sup>See table I.

<sup>b</sup>PM = parent material. WSOC = weld shear on cooling at zero load.

<sup>c</sup>FOL = failed on loading.

TABLE III. - TENSILE-SHEAR TEST RESULTS FOR SINGLE-SPOT LAP JOINTS IN 0.4-MILLIMETER (0.015-IN.) TD-NiCr SHEET AT ROOM TEMPERATURE AND AT 1100° C

[All specimens were postheated at 1200° C for 2 hr in hydrogen prior to testing.]

| Weld schedule <sup>a</sup><br>and number | Fracture load |     | Weld shear stress<br>at fracture |      | Fracture <sup>b</sup>      |
|--|---------------|-----|----------------------------------|------|----------------------------|
|  | N             | lb  | MN/m <sup>2</sup>                | ksi  |                            |
| 1100° C Tests                            |               |     |                                  |      |                            |
| A-5                                      | 800           | 180 | 49.9                             | 7.22 | PM, away from weld         |
| A-6                                      | 711           | 160 | 44.4                             | 6.42 | PM, away from weld         |
| B-8                                      | 631           | 142 | 38.2                             | 5.52 | Weld shear, partial button |
| B-9                                      | 666           | 150 | 40.3                             | 5.84 | Weld shear                 |
| C-6                                      | 578           | 130 | 23.4                             | 3.38 | PM, away from weld         |
| C-7                                      | 556           | 125 | 22.5                             | 3.26 | Weld shear                 |
| D-11                                     | 467           | 105 | 35.2                             | 5.10 |                            |
| D-12                                     | 445           | 100 | 33.4                             | 4.85 |                            |
| D-13                                     | 365           | 82  | 27.5                             | 3.98 |                            |
| Room-temperature tests                   |               |     |                                  |      |                            |
| A-7                                      | 2650          | 595 | 165                              | 23.9 | Button pullout             |
| A-8                                      | 3120          | 700 | 194                              | 28.1 |                            |
| A-9                                      | 3140          | 705 | 195                              | 28.3 |                            |
| A-10                                     | 3090          | 695 | 193                              | 27.9 |                            |
| B-10                                     | 3180          | 715 | 192                              | 27.8 |                            |
| B-11                                     | 3120          | 700 | 188                              | 27.2 |                            |
| C-8                                      | 3250          | 730 | 131                              | 19.0 |                            |
| C-9                                      | 3400          | 765 | 137                              | 19.9 |                            |
| D-14                                     | 2770          | 622 | 208                              | 30.2 |                            |
| D-15                                     | 2850          | 640 | 215                              | 31.1 |                            |
| D-16                                     | 2850          | 640 | 215                              | 31.1 |                            |

<sup>a</sup>See table I.

<sup>b</sup>PM = parent material.

TABLE IV. - ROOM-TEMPERATURE TENSION-TENSION ( $\sigma_{\min}/\sigma_{\max} = 0.2$ )  
 FATIGUE DATA FOR SINGLE-SPOT LAP JOINTS IN 0.4-MILLIMETER  
 (0.015-IN.) TD-NiCr SHEET

[All specimens were postheated at  $1200^{\circ}\text{C}$  for 2 hr in hydrogen prior to testing.]

| Weld schedule <sup>a</sup><br>and number | Load    |     |         |    | Weld shear stress |      |                   |      | Cycles to<br>failure |  |
|--|---------|-----|---------|----|-------------------|------|-------------------|------|----------------------|--|
|  | Maximum |     | Minimum |    | Maximum           |      | Minimum           |      |                      |  |
|  | N       | lb  | N       | lb | MN/m <sup>2</sup> | ksi  | MN/m <sup>2</sup> | ksi  |                      |  |
| A-11                                     | 1890    | 425 | 378     | 85 | 118               | 17.1 | 23.6              | 3.42 | 2 900                |  |
| A-12                                     | 1450    | 325 | 289     | 65 | 90.4              | 13.1 | 18.0              | 2.61 | 9 300                |  |
| A-13                                     | 1000    | 225 | 200     | 45 | 62.2              | 9.04 | 12.5              | 1.81 | 28 000               |  |
| A-14                                     | 800     | 180 | 160     | 36 | 49.8              | 7.23 | 10.0              | 1.45 | 47 300               |  |
| A-15                                     | 555     | 125 | 111     | 25 | 34.6              | 5.02 | 6.9               | 1.00 | 258 700              |  |
| B-12                                     | 1890    | 425 | 378     | 85 | 114               | 16.5 | 22.8              | 3.31 | 5 200                |  |
| B-13                                     | 1560    | 350 | 312     | 70 | 93.9              | 13.6 | 18.8              | 2.72 | 15 500               |  |
| B-14                                     | 1110    | 250 | 222     | 50 | 67.1              | 9.73 | 13.5              | 1.95 | 60 100               |  |
| B-15                                     | 845     | 190 | 169     | 38 | 51.0              | 7.39 | 10.2              | 1.48 | 109 000              |  |
| B-16                                     | 670     | 150 | 134     | 30 | 40.3              | 5.84 | 8.1               | 1.17 | 510 000              |  |
| B-17                                     | 535     | 120 | 107     | 24 | 32.2              | 4.67 | 6.4               | .93  | b 946 000+           |  |
| C-10                                     | 1960    | 440 | 392     | 88 | 79.4              | 11.5 | 16.4              | 2.39 | 7 800                |  |
| C-11                                     | 1560    | 350 | 312     | 70 | 62.8              | 9.10 | 12.6              | 1.82 | 38 900               |  |
| C-12                                     | 890     | 200 | 178     | 40 | 35.9              | 5.20 | 7.2               | 1.04 | 480 700              |  |
| C-13                                     | 780     | 175 | 156     | 35 | 31.5              | 4.56 | 6.1               | .91  | 401 600              |  |
| C-14                                     | 670     | 150 | 134     | 30 | 26.9              | 3.90 | 5.4               | .78  | b 1 000 000+         |  |
| D-17                                     | 1340    | 300 | 267     | 60 | 101               | 14.6 | 20.1              | 2.91 | 3 500                |  |
| D-18                                     | 1110    | 250 | 222     | 50 | 83.5              | 12.1 | 16.8              | 2.43 | 8 200                |  |
| D-19                                     | 710     | 160 | 142     | 32 | 53.6              | 7.76 | 10.7              | 1.55 | 77 900               |  |
| D-20                                     | 535     | 120 | 107     | 24 | 40.2              | 5.82 | 8.0               | 1.16 | 120 600              |  |
| D-21                                     | 535     | 120 | 107     | 24 | 40.2              | 5.82 | 8.0               | 1.16 | 265 300              |  |
| D-22                                     | 445     | 100 | 89      | 20 | 33.5              | 4.85 | 6.7               | .97  | 740 300              |  |

<sup>a</sup>See table I.

<sup>b</sup>Test stopped.

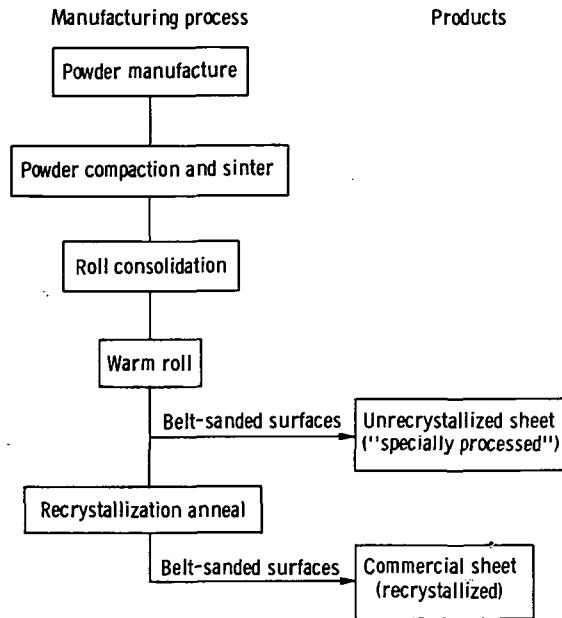


Figure 1. - Manufacturing process for TD-NiCr sheet. (From ref. 3).

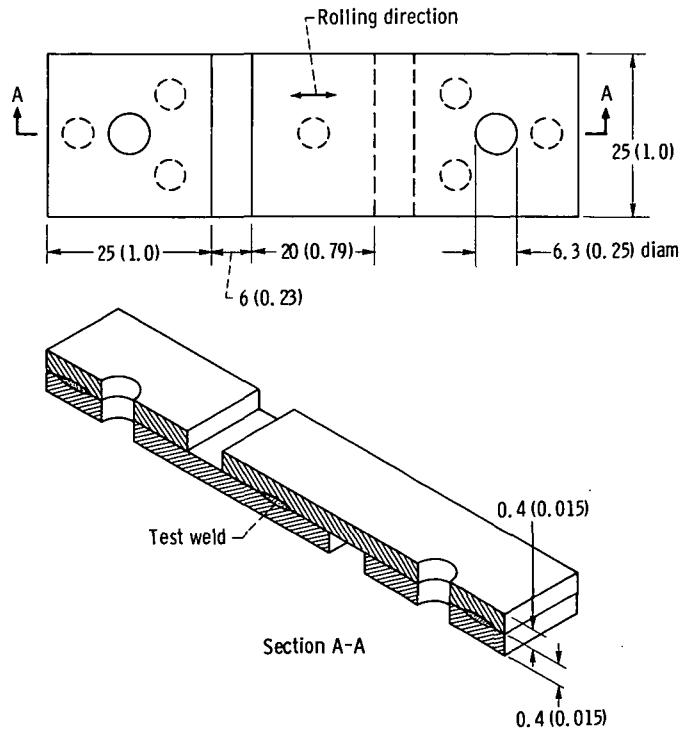


Figure 2. - Resistance spot-weld lap joint specimen used for tensile-shear, stress-rupture shear, and fatigue tests. Reinforcing tabs are spot welded to the test specimen to prevent failure at the pin holes. Dimensions are in millimeters (in.). Section A-A was used for metallographic examination of the test weld.

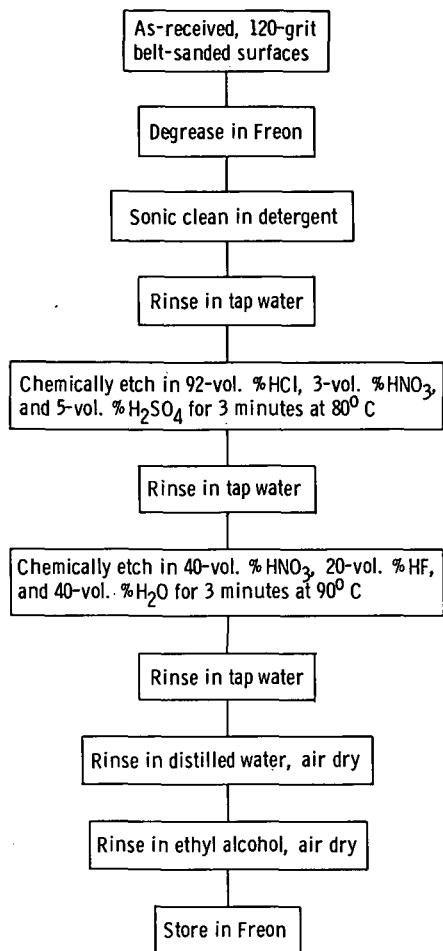


Figure 3. - Flow diagram showing faying-surface preparation procedure used for specimens welded under schedules A, B, and C.

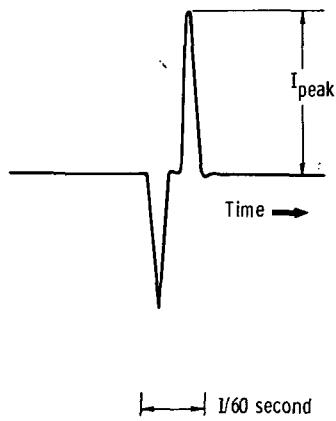


Figure 4. - Typical welding current trace for resistance spot weld made with 400-kilovolt-ampere, single-phase resistance-spot-welding machine. This current trace is representative of the one-cycle schedule B welds in 0.4-millimeter (0.015 in.) TD-NiCr sheet.

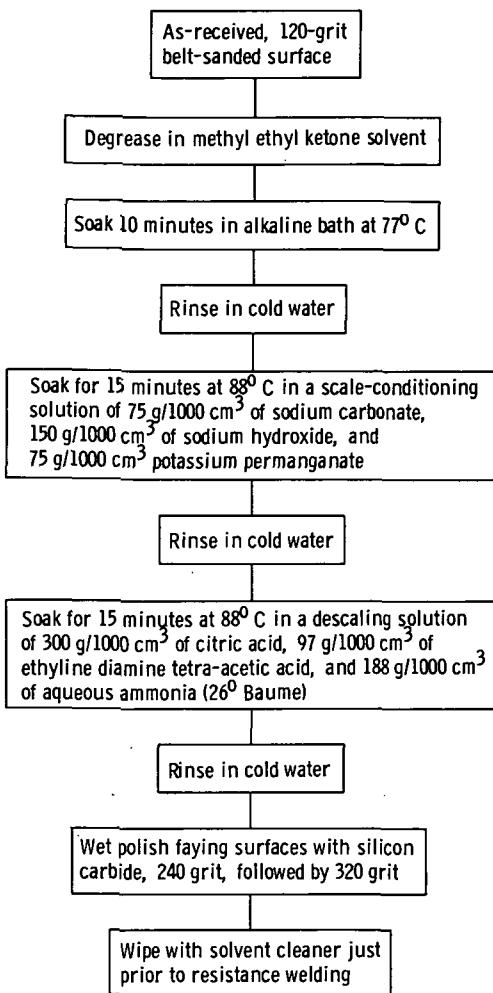


Figure 5. - Flow diagram showing faying-surface preparation procedures used for specimens welded under schedule D.

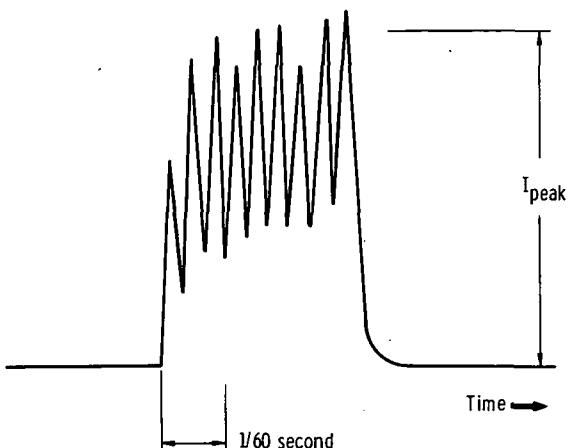
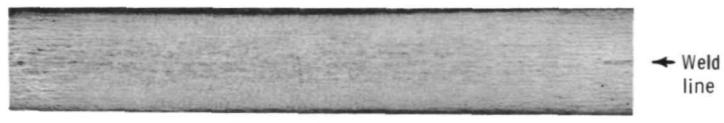
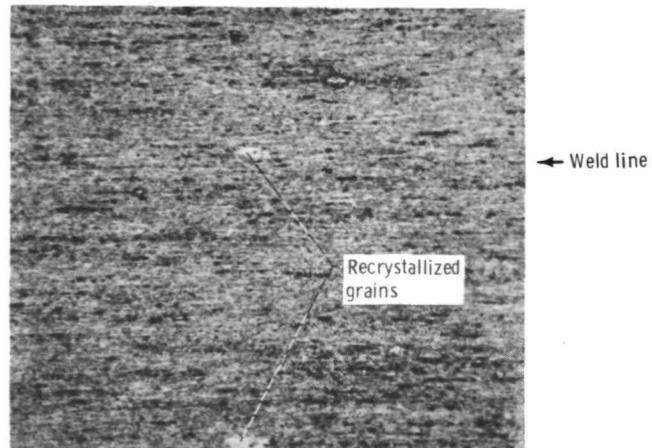


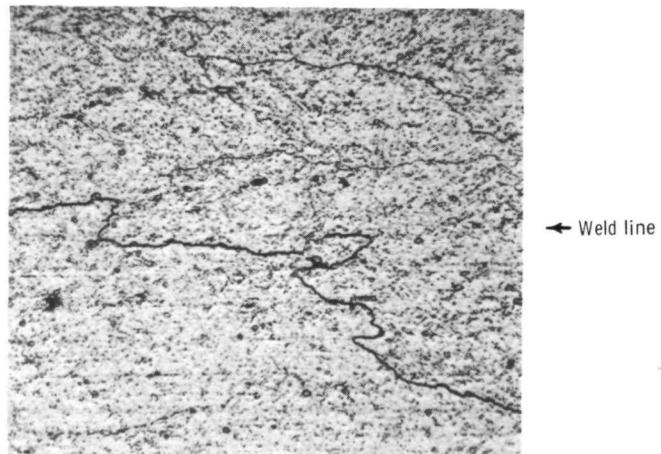
Figure 6. - Typical welding current trace for resistance spot weld made with 100-kilovolt, three-phase resistance welding machine. This current trace is representative for single-impulse, schedule D lap welds in 0.4-millimeter (0.015 in.) TD-NiCr sheet.



(a) As-welded macrostructure. X24.



(b) As-welded microstructure. X500.



(c) Postheated microstructure ( $1200^{\circ}$  C, 2 hr.). X500.

Figure 7. - Typical schedule A solid-state spot welds in specially processed TD-NiCr sheet.

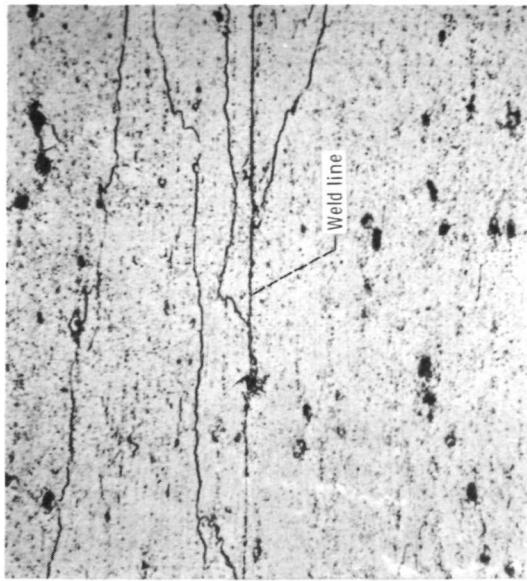
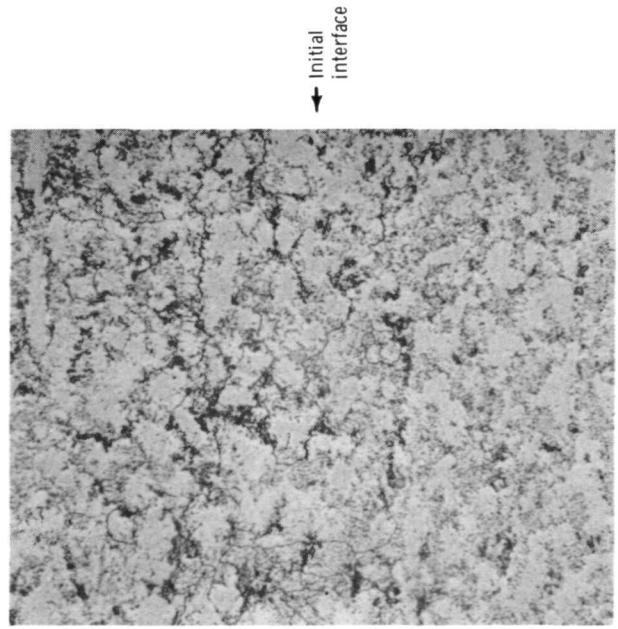
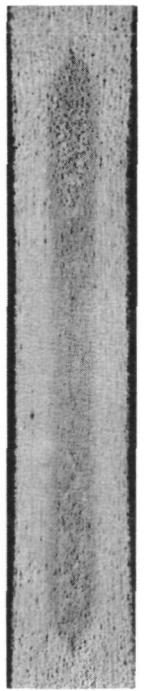
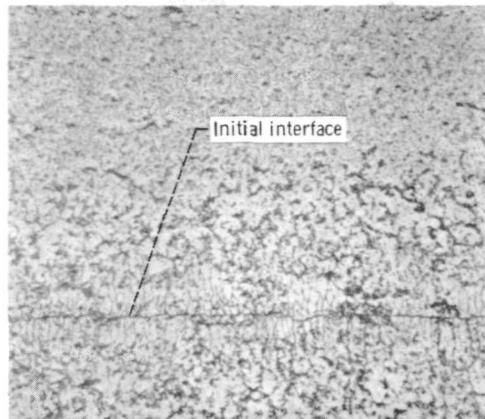


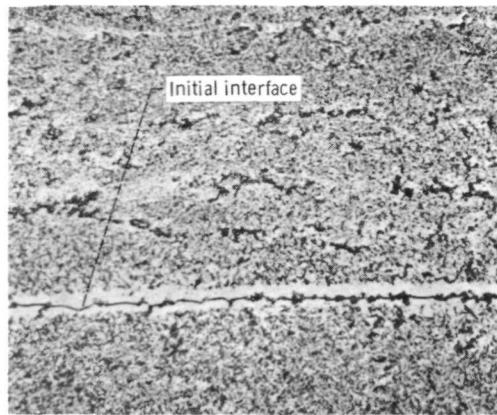
Figure 8. - Typical schedule B fusion spot weld in commercial TD-NiCr sheet.  
Figure 9. - Typical schedule C solid-state spot weld in commercial Td-NiCr sheet.



(a) As-welded macrostructure. X24.

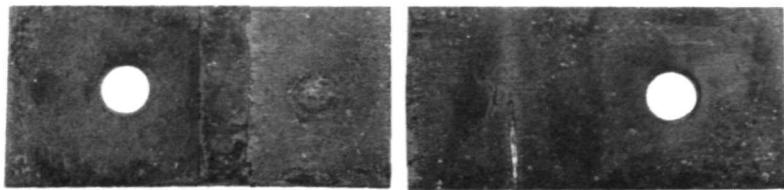


(b) As-welded microstructure. X500.

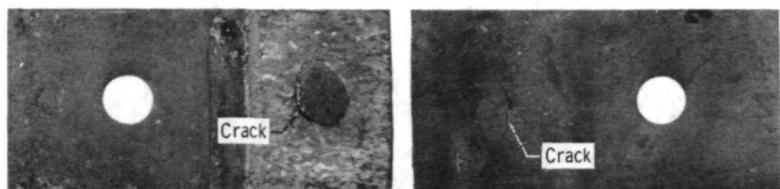


(c) Postheated microstructure ( $1200^{\circ}\text{C}$ , 2 hr). X500.

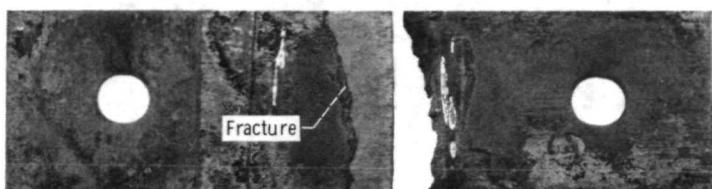
Figure 10. - Typical schedule D fusion spot weld in commercial TD-NiCr sheet.



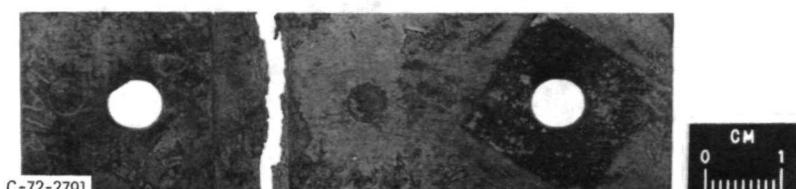
(a) Shear at weld.



(b) Shear at weld and parent material cracks.



(c) Parent-material failure near spot weld.



(d) Parent-material failure away from spot weld.

Figure 11. - Fracture appearance of tested 1100<sup>0</sup> C stress-rupture shear specimens (single-spot lap welds in 0.4-mm (0.015-in.) TD-NiCr sheet).

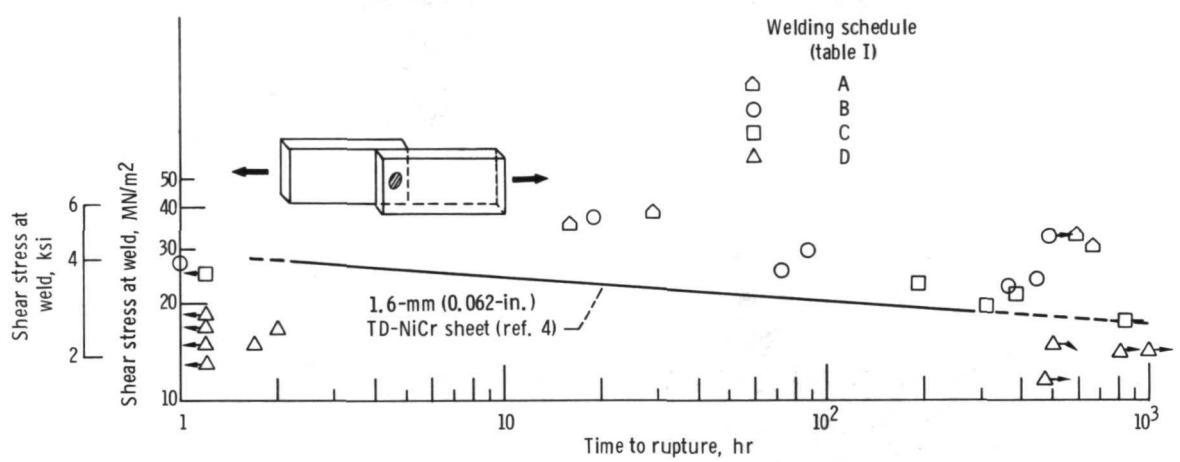


Figure 12. - Comparison of shear stress-rupture lives for schedule A, B, C, and D lap welds. Single-spot weldments in 0.4-millimeter (0.015-in.) TD-NiCr sheet were postheated at  $1200^{\circ}\text{C}$  for 2 hours prior to testing.

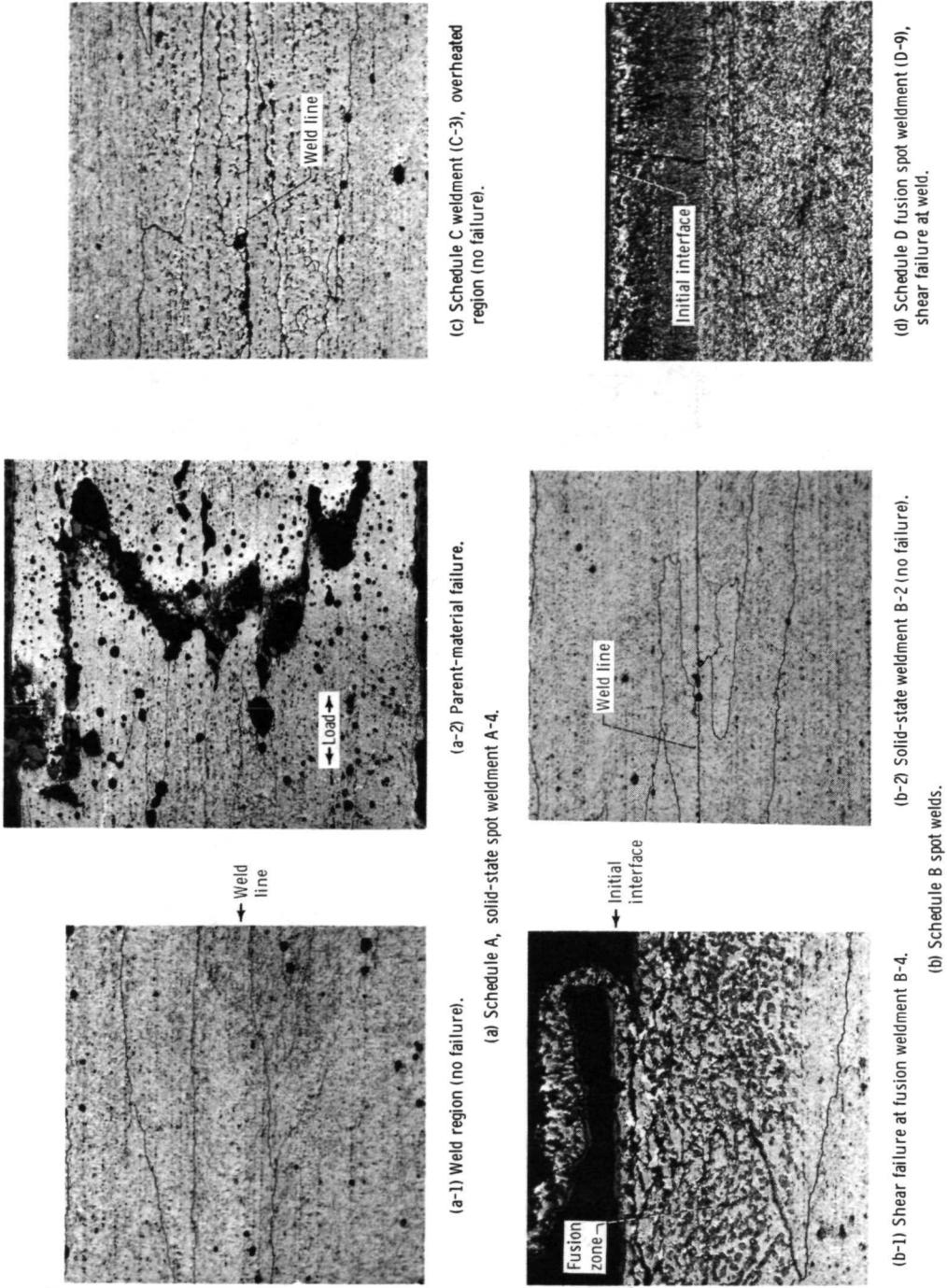


Figure 13. - Tested 1100° C stress-rupture shear lap weldments in TD-NiCr sheet. X250.

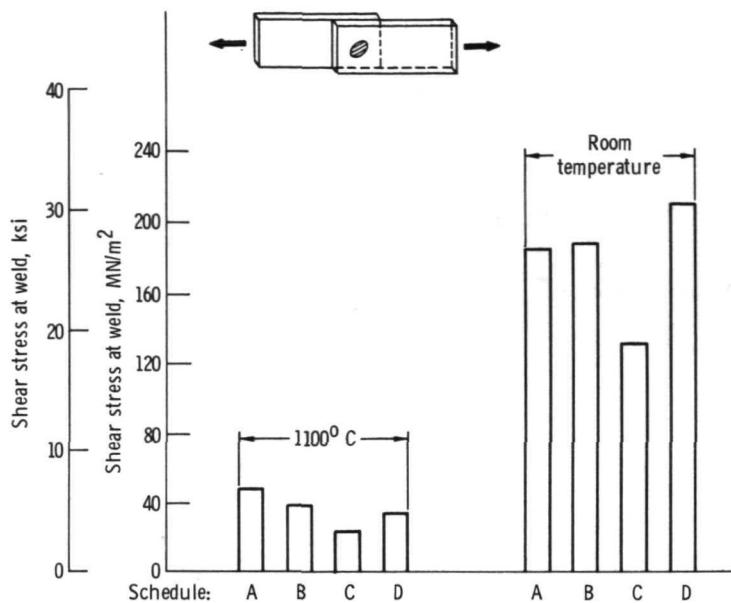
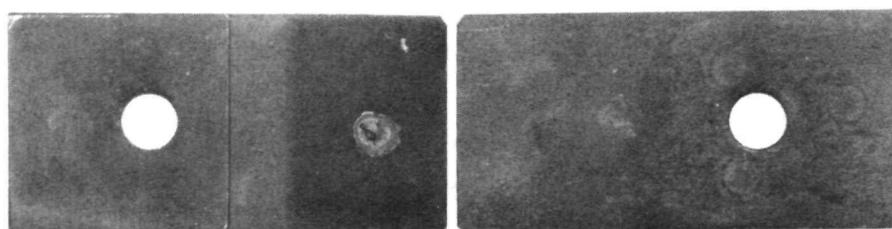


Figure 14. - Comparison of tensile-shear test results for schedule A, B, C, and D lap welds. Single-spot weldments in 0.4-millimeter (0.015-in.) TD-NiCr sheet were postheated at  $1200^{\circ}\text{C}$  for 2 hours prior to testing.



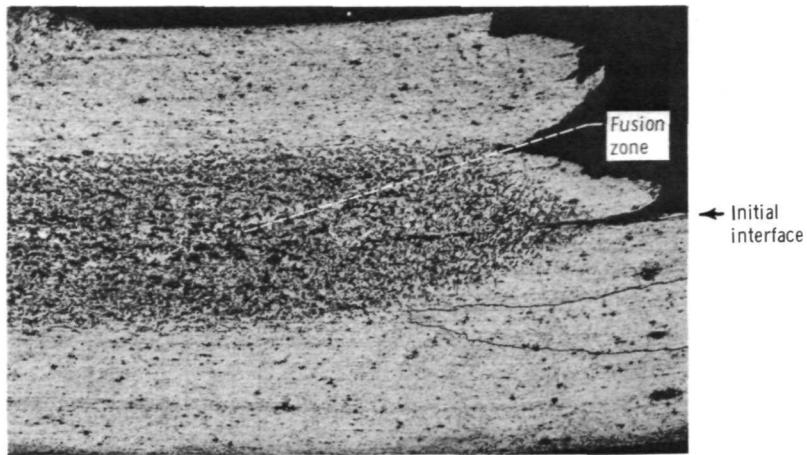
(a) Shear at weld.



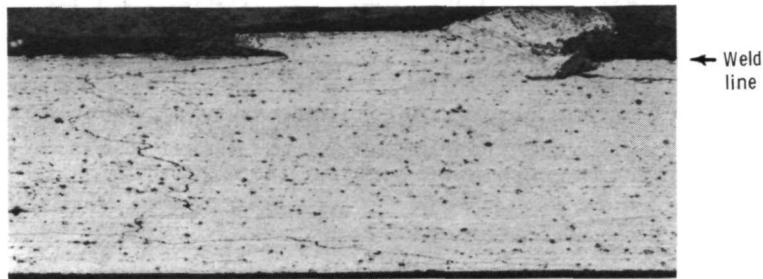
C-72-2790

(b) Parent-material failure away from spot weld.

Figure 15. - Fracture appearance of tested  $1100^{\circ}\text{C}$  tensile-shear specimens (single-spot lap welds in 0.4-mm (0.015-in.) TD-NiCr sheet).



(a) Schedule B fusion spot weldment (B-8), partial button failure.



(b) Schedule C solid-state spot weldment (C-7), shear at weld.

Figure 16. - Failure of  $1100^{\circ}$  C tensile-shear lap weldments in TD-NiCr sheet. X100.

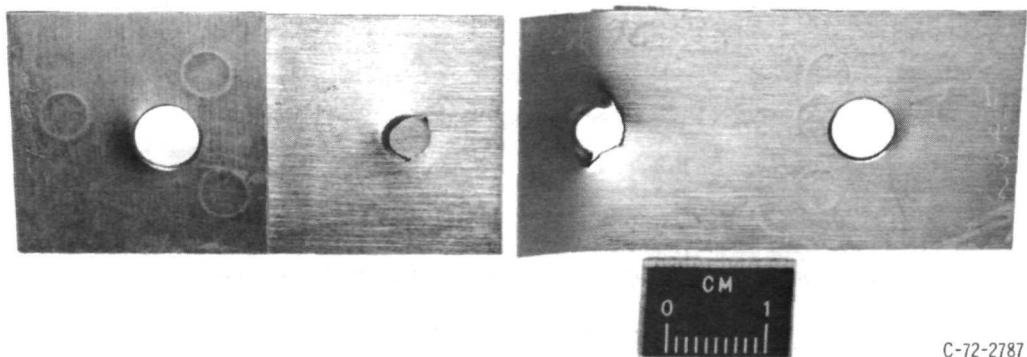


Figure 17. - Typical button pullout failure in room-temperature tensile shear test specimens. Single-spot weldments in 0.4 mm (0.015-in.) TD-NiCr sheet were postheated at  $1200^{\circ}$  C for 2 hours prior to testing.

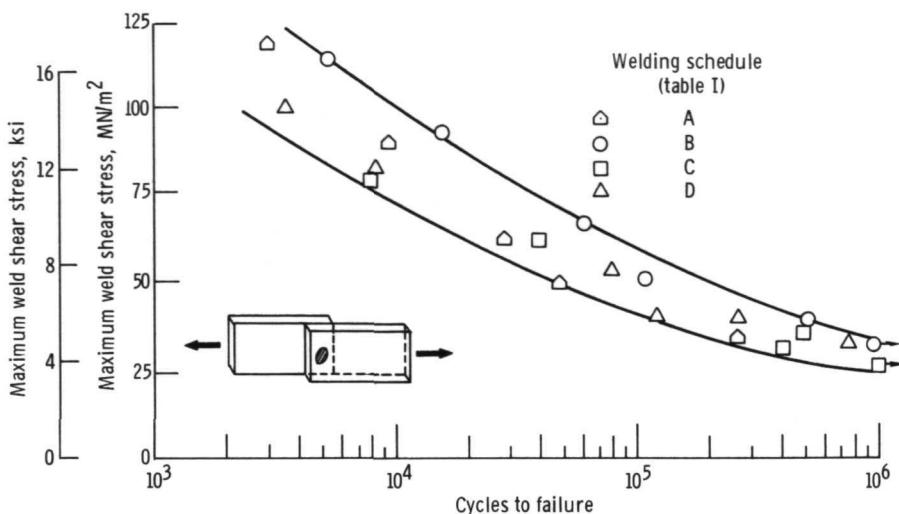


Figure 18. - Room-temperature fatigue strength of schedule A, B, C, and D resistance spot welds. Single-spot lap welds in 0.4-millimeter (0.015-in.) TD-NiCr sheet were postheated at 1200° C for 2 hours in hydrogen prior to testing. Tension-tension loading,  $\sigma_{\min}/\sigma_{\max} = 0.2$ .

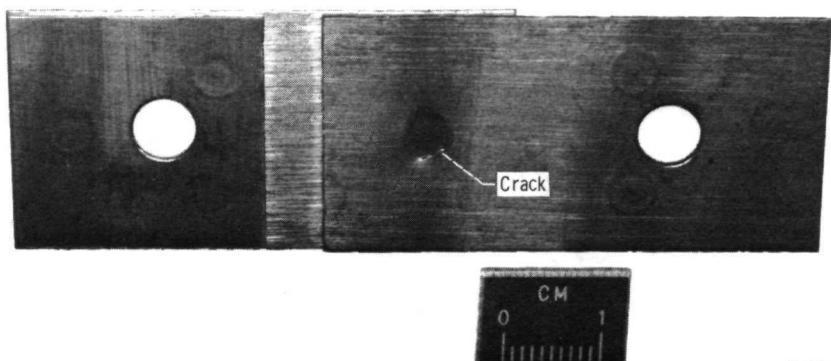
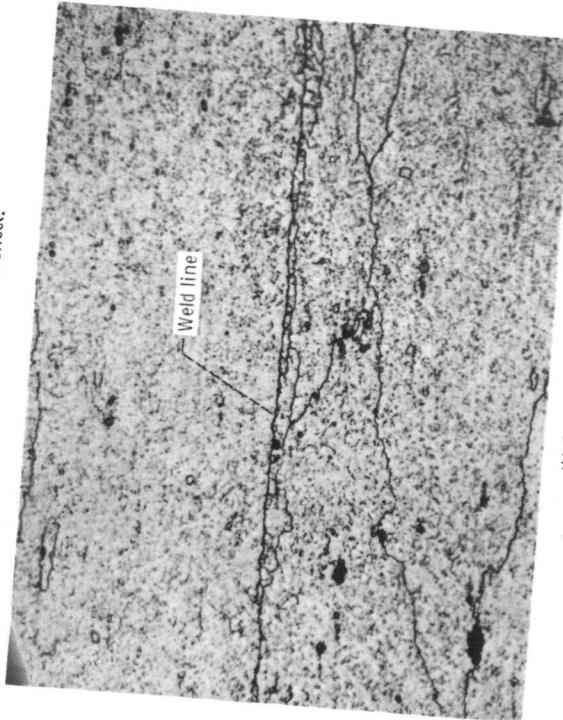


Figure 19. - Typical fatigue crack in resistance-spot-welded 0.4-mm (0.015-in.) TD-NiCr sheet. The crack is in the parent material at the periphery of the weld. Testing was done at room temperature in the postheated condition (1200° C for 2 hr).



(a) Specially processed sheet.



(b) Commercial sheet.

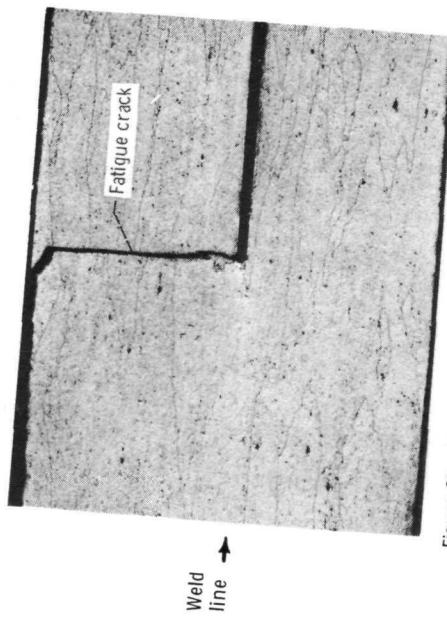


Figure 20. - Transgranular, room-temperature, fatigue failure in single-spot lap weldment (A-13) in 0.4-millimeter (0.015-in.) TD-Nicr sheet. Testing was done in the post-heated condition (1200°C for 2 hr). X100.

Figure 21. - Solid-state resistance spot welds in 1.6-millimeter (0.062-in.) TD-Nicr sheet post-heated at 1200°C for 2 hours in hydrogen. X500.

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